SMALL SPOT SPECTROSCOPIC ELLIPSOMETER
WITH REFRACTIVE FOCUSING

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PRIORITY

This application claims priority from prior provisional application Serial No. 60/204,253 filed May 15, 2000.

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Technical Field

The subject invention relates to spectroscopy ellipsometry. More specifically, the subject invention relates to an ellipsometer which utilizes an all-refractive optics

15   system for focusing a broadband probe beam onto a sample.

Background of the Invention

Ellipsometry is a powerful technique for evaluating thin films on semiconductors. In any ellipsometer, a probe beam having a known polarization state

20   is directed to interact with a sample. Changes in the polarization state induced by the interaction of the probe beam with the sample are then monitored. This information, in the form of Ψ and Δ measurements, is used to analyze characteristics of the sample.

It is well known that in order to improve an ellipsometric analysis, some form of multiple measurements are desirable. This can include taking measurements at

25   multiple angles of incidence or at multiple wavelengths. Spectroscopic ellipsometers using monochrometers to scan the wavelength have been known for many years. For example, see "High Precision Scanning Ellipsometer," by Aspnes and Studna, Applied Optics, Vol. 14, No. 1, January 1975.

More recently, efforts have been made to expand the desired wavelength range

30   of spectroscopic ellipsometers into the UV and to obtain measurement data at multiple wavelengths simultaneously. When used in the semiconductor field, broadband probe beams must be focused to a relatively small spot size on the sample surface. Attempts to use lenses (refractive optics) to focus broadband probe beams, and particularly

those including UV wavelengths, have run into problems. First, lenses typically have chromatic aberrations. Such aberrations cause the focused distance to be different for different wavelengths. Another problem with lenses is that it was often difficult to find lens materials with good transmission characteristics across a broad wavelength

5   range.

Due to these difficulties, researchers in the prior art began using curved mirrors to focus the broadband probe beam onto the sample surface. Mirrors are advantageous since they can be highly reflective across a broad range of wavelengths. In addition, mirrors exhibit little or no chromatic aberrations. The use of focusing mirrors for a

10   broadband ellipsometer are described in patents, No. 4,790,659, issued December 1988, to Erhman, and No. 5,608,526, issued March 4, 1997, to Piwonka-Corle.

Unfortunately, while providing a solution for chromatic aberration, mirrors are relatively difficult to align. More specifically, since mirrors must be focused off-axis, any angular error in alignment creates twice that error in beam position. Further, if the

15   mirror is removed from the optics path, a light beam cannot be used to align the rest of the optics path since the mirror is needed to turn the beam. In contrast, the elements of an optics system can be aligned when a focusing lens is removed from the beam path. Another problem with mirrors is that when the probe beam reflects off the mirror, the polarization state of the beam is changed. Such changes must be very accurately and

20   precisely characterized, otherwise they will cause errors in the analysis of the sample.

Accordingly, it would be desirable to have an all-refractive (lens-based) system for focusing a broadband probe beam to a small spot onto a sample surface. Such a system would be easier to align. In addition, any polarization changes in the probe beam induced by the lens system can be more accurately controlled.

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Summary of the Invention

In accordance with these objects, the subject invention provides for a spectroscopic ellipsometer which can obtain a small focused beam spot on a sample using all-refractive optics. The spectroscopic ellipsometer is of the type which has at

30   least one broadband light source emitting both UV and visible wavelengths. The

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source typically has a range of at least 500nm and preferably covers a wavelength range of about 200nm to 800nm.

Light from the broadband source is polarized and then focused onto the sample with an all-refractive optical system. The optical system includes at least two lenses which are transmissive in the UV and visible wavelengths. The curvatures of the lenses are selected to minimize chromatic and spherical aberrations. With respect to the chromatic aberration compensation, the variation in the focal point over the wavelength range (focal shift) should be no more than five percent and preferably less than 2.5 percent of the mean focal length of the optical system. The optical system is intended to focus the beam on the sample to a small spot, on the order of 3mm or less.

An analyzer system is provided for monitoring the change in polarization state of the reflected beam induced by interaction with the sample. Any conventional analyzer can be used, including rotating analyzer or rotating compensator (waveplate) configurations. In the preferred embodiment, an aperture or spatial filter is provided in the path of the reflected beam to limit the area of the sample investigated. In the preferred embodiment, the spatial filter includes a focusing optical element and an aperture configured to limit the measured region to a spot size of 100 microns or less.

By using an all-refractive optical system for focusing the beam on the sample, problems associated with the alignment of mirrors are eliminated. In addition, the problems associated with changes in the polarization state of the beam induced by the mirrors are also eliminated.

Further objects and advantages will be apparent from the following detailed description taken in conjunction with the drawings in which:

Brief Description of the Drawings

Figure 1 is a schematic illustration of a basic lay-out of the optical elements of a broadband ellipsometer of the subject invention.

Figure 2 is a schematic illustration of a spectrometer configuration for obtaining simultaneous measurements at a plurality of wavelengths.

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Figure 3 is a cross-sectional view of an all-refractive optical system for focusing a broadband probe beam on a sample.

Figure 4 is an exploded perspective view of the optical elements of Figure 3.

5 **Detailed Description of the Preferred Embodiment**

Referring to Figure 1, a broadband ellipsometer 10 formed in accordance with the subject invention is illustrated. The ellipsometer includes a light source 12 for generating a polychromatic beam having both UV and visible wavelengths. This light source can be defined by a single lamp, or by two lamps such as a tungsten halogen

10 for the visible range and a deuterium lamp for the UV wavelengths. The source would typically have a range of at least 500nm and preferably covers a range from about 200nm to 800nm.

In the preferred embodiment, the light is directed through a polarizer 14 for establishing a fixed, known polarization of the light. The light is then directed into the

15 all-refractive lens system 16 of the subject invention, either directly or via one or more turning mirrors 17. These turning mirrors would be essentially planar (flat), rather than curved. The lens system 16 focuses the light on the sample 8.

The light reflected from the sample is collimated by collimator 30. It is passed to an analyzer system for determining the change in polarization state of the beam. In

20 the illustrated embodiment, the analyzer system includes a rotating waveplate (compensator) 18, a stationary analyzer (polarizer) 20 and a detector 24. The waveplate is driven by motor 19. As seen in Figure 2, the detector is a spectrometer which includes an optical element 28 for dispersing the light (i.e. a grating) and a diode array 29 to measure the different wavelengths simultaneously. As discussed

25 further below, imaging optics, including a focusing element 23 and an aperture 22 can be provided as an input to the detector for controlling the size of the spot on the sample surface which is actually measured. A processor 26 receives the output signals from the detector.

The basic operation of the subject ellipsometer is similar to other broadband

30 ellipsometers and need not be discussed herein. Further information can be obtained

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from prior patents and applications: 5,877,859; 5,608,526; WO99/02970, all incorporated herein by reference. As can be seen, there are a number of variations in light sources and beam detection (spectrometer) systems. In addition, there are a number of approaches possible for extracting ellipsometric information including

5   rotating polarizers, analyzers and compensators. These elements can be continuously rotated or indexed. In addition, the ellipsometer can be operated as a nulling ellipsometer. The subject invention is intended to be applied to any of these embodiments all of which are well known and understood by those skilled in the art.

These various types of ellipsometers can be modified in accordance with the

10   subject invention to include an all-refractive focusing system. A preferred version of such a focusing system is illustrated in Figures 2 and 4. This embodiment is defined by a three lens triplet consisting of a pair of calcium fluoride lenses 42, 46 and one fused silica lens 44. These lens materials are substantially transparent in the wavelength region of interest. In the preferred embodiment, the materials are at least

15   97% transmissive from 190nm to 900nm.

At least two lenses of different materials are necessary in order to reduce the chromatic aberration of the system. Chromatic aberration is observed when the focal point for one wavelength is different from the focal point for another wavelength. In a broadband focused system, chromatic aberration has the effect of smearing out the

20   spot on the sample and reducing the amount of light which can be detected and analyzed. The amount of variation in the focal point with respect to the wavelength should be less than five percent of the mean focal length over the range of wavelengths and preferably is less than 2.5 percent.

Chromatic aberration can be reduced by increasing the number of lenses.

25   However, adding lenses can give rise to other problems. Obviously, as more lenses are used, the cost of the optical system will increase. In addition, since each lens can cause polarization changes if not carefully mounted, the complexity of the assembly procedure increases. It is believed that a three lens system strikes a good balance between these countervailing issues. It should be understood that the scope of the

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subject invention is intended to cover a two lens system as well as systems with four

or more lenses.

In the preferred embodiment, lens 42 is positioned on the upstream side of the

system and first receives the probe light beam. Lens 42 is a calcium fluoride convex

5   lens. Lens 44 is a fused silica concave lens while lens 46 is a calcium fluoride convex

lens. The respective radii of curvature of these lenses and their focal lengths (at 300

nm) are set forth in the table below where the front surface is the face which first

receives the probe beam radiation and rear surface is the face where the probe beam

emerges.

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Table 1

| | Radius of Curvature (mm) | | Center | | Focal Length |
	Front Surface	Rear Surface	Thickness	Material	@ 300nm [mm]
Lens 42	62.7	20.1	5mm	CaF_2	34.2
Lens 44	18.7	70.1	1.5mm	Fused Silica	-25.2
Lens 46	33.3	105.4	4mm	CaF_2	56.2

The spacing between lens 42 and 44 is 1.04mm. The spacing between lens 44

and 46 is 1.49mm.

25   The lenses are mounted in a fixture which stabilizes the lenses and minimizes

the stress on the lenses. The optical assembly includes a stainless steel housing 41

with a radial lip 52 on the front end thereof to hold lens 42 in place. Precision metal

spacers 43 and 45, formed from an aluminum alloy, separate lenses 42 and 44 and 44

and 46 respectively. A Viton O-ring 47 is sandwiched between the rear surface of lens

30   46 and retainer ring 48. Retainer ring is threadably engaged with the housing 41.

Proper mounting is important for minimizing stress in the lenses. These

stresses induce birefringence which can change the polarization state of the probe

beam. These stresses can be minimized if the lens mount does not vary significantly

in shape or size due to temperature variations. Stress can also be minimized by using

soft materials which contact the lens or by selecting materials and dimensions so that the expansion of the mounts matches the expansion of the lens. In the preferred embodiment, the shape of the spacers is matched to the shape of the lenses so there are no sharp corners hitting the lenses. In addition, the flexible O-ring 47 prevents the

5   lenses from shifting, but provides relief for thermal expansion.

In practice, it has been observed that any stresses that arise in the lenses tend to run generally transversely across the lens. Accordingly, applicant has found that the effect of any residual stress in the lens can be minimized if the axis of the transverse stress is aligned with the axis of the polarizer and/or analyzer of the ellipsometer. An

10 empirical measurement of the lens is made, for example, by using the lens as a sample in a transmissive ellipsometer. The axis of the stress is then noted on the lens and referred to during assembly procedures.

The optical system 16 is intended to create a relatively small spot on the sample surface. For semiconductor applications, the spot size should be less than

15 3mm and preferably about 1.5 mm in diameter. In the illustrated embodiment, the system will actually create two spatially separate spots of different polarization states. This is because the polarizer 14 is a Rochon prism which causes one polarization to be angularly deviated with respect to the other polarization such that two separate beams are created. Each beam is focused at a spatially separate spot on the sample.

20 The imaging optics are arranged to collect light from only one of the two spots. The imaging optics includes the collimator 30, focusing mirror 23 and the aperture 22. Focusing mirror 23 relays an image of the sample into the plane of the aperture 22. The aperture 22 is sized to transmit only a small portion of the illuminated area. In the preferred embodiment, the area imaged should be less than 100 microns and

25 preferably on the order of 60 microns.

Analysis of the data can be performed using conventional modeling approaches. For example, a theoretical model is set up which corresponds to the actual sample, including a substrate and one or more thin film layers. This model is then used in conjunction with the Fresnel equations to calculate expected measurement

30 data. This theoretical calculated data is then compared to the actual measured data.

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Differences between the calculated data and the actual measured data are then used to vary the expected characteristics of the sample in an iterative process for determining the actual composition of the sample.

While the subject invention has been described with reference to a preferred

5   embodiment, various changes and modifications could be made therein, by one skilled in the art, without varying from the scope and spirit of the subject invention as defined by the appended claims